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A new rocket engine design concept has been proposed that combusts a portion of the propellant flow in the nozzle section. This concept which is called Thrust Augmented Nozzle (TAN) allows for higher thrust at takeoff and a more optimum nozzle design that avoids flow separation at sea level conditions. The TAN injector is a cooled nozzle section downstream of the throat that injects propellants that combust and provides additional thrust. The TAN injector has similar design issues associated with conventional rocket engine injectors with the additional design challenge of combustion products flowing over the TAN injector. In order to demonstrate this new engine design concept, Aerojet designed, manufactured, and hot fire tested a subscale version of this engine. The thermal design process and results are presented herein. The derivation of gas side boundary conditions are based on test data and CFD analysis. The coolant side boundary conditions are based on conventional correlations for the propellants. Test data are also presented.

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Thermal Design and Analysis of the Thrust Augmented Nozzle (TAN) Injector (Preprint)

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A new rocket engine design concept has been proposed that combusts a portion of the propellant flow in the nozzle section. This concept which is called Thrust Augmented Nozzle (TAN) allows for higher thrust at takeoff and a more optimum nozzle design that avoids flow separation at sea level conditions. The TAN injector is a cooled nozzle section downstream of the throat that injects propellants that combust and provides additional thrust. The TAN injector has similar design issues associated with conventional rocket engine injectors with the additional design challenge of combustion products flowing over the TAN injector. In order to demonstrate this new engine design concept, Aerojet designed, manufactured, and hot fire tested a subscale version of this engine. The thermal design process and results are presented herein. The derivation of gas side boundary conditions are based on test data and CFD analysis. The coolant side boundary conditions are based on conventional correlations for the propellants. Test data are also presented.

Nomenclature

FEA = Finite Element Analysis
GOX = Gaseous Oxygen
LOX = Liquid Oxygen
RP-1 = Rocket Engine Grade Kerosene
TAN = Thrust Augmented Nozzle

I. Introduction

One of the key issues facing designers of launch vehicle rocket engines is the selection of the nozzle exit area ratio. Typically designers trade off required high thrust at launch atmospheric back pressure conditions with the desire for higher performance at altitude with very little back pressure. Typical designs often result in some flow separation at sea level conditions and reduced specific impulse at higher altitudes. Aerojet's patented TAN concept[1] eliminates the needs for such tradeoffs by injecting and combusting propellants in the divergent section of the nozzle. The use of TAN propellants at sea level conditions results in a higher thrust level at sea level conditions without impacting the main chamber design. At higher altitudes the TAN propellant flow rate can be tailored or eliminated resulting in increased specific impulse. The TAN operation mode is shown in Fig. 1. The benefits of the TAN concept for new designs or retrofitting of existing designs has been documented previously[2].

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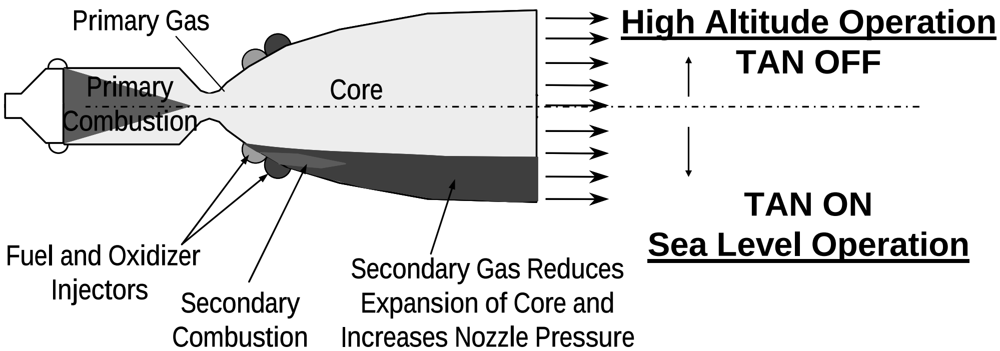

Figure 1. TAN Operational Modes

In order to demonstrate this new engine design concept Aerojet designed, manufactured, and hot fire tested a subscale version of the engine. One of the unique features of this design concept is that different propellants can be used for the TAN propellants and the main chamber propellants. For this demonstration testing the main propellants were gaseous hydrogen and gaseous oxygen (GOX) and an injector from the LANTR program[3] was used. The TAN injector was attached downstream of the throat.

The TAN injector utilized Aerojet's platelet design technology. Platelet designs are based on etching detailed flow passages on thin sheets of metals which are bonded together to form a monolithic structure. The use of Aerojet's platelet designs for many different types of thermal management applications is described in Reference 4. The TAN propellant combination for this subscale demonstration was LOX and RP-1. The TAN injector also had a water cooling circuit to provide cooling during main injector operation without any TAN propellant flow. A water cooled nozzle was attached downstream of the TAN injector to obtain performance data at an area ratio more representative of a launch engine.

Thermal analysis was conducted on the TAN injector to ensure thermal integrity of the TAN injector. Thermal analysis was conducted to ensure that there was adequate cooling margin for the water coolant circuit. Since the coolant water was subcritical, the possibility existed that if the heat flux to the coolant exceeded the critical heat flux, the water coolant would transition to film boiling. The heat transfer rate to the water coolant would have been dramatically reduced if it were to transition to film boiling undoubtly resulting hardware damage. Aerojet has extensive experience designing many water cooled devices for high heat flux environments. Thermal analysis was also conducted to insure that the RP-1 propellant injection circuit maintained a wall temperature below its coking design limit. Temperature predictions were made to allow structural evaluation of the hardware for pressure loading and also cycle life based on low cycle fatigue criteria.

II. Hardware Description

The test hardware is shown in Fig. 2 and includes the four major components: main injector, main combustion chamber, TAN injector, and cooled nozzle extension. The main injector was used previously on another test program and its performance was well characterized. The main combustion chamber is a gun drilled water cooled copper chamber design similar to a previous chamber design though the expansion area ratio was changed to accommodate the current TAN design. The TAN injector has two propellant circuits and a water coolant circuit. The TAN injector also had pressure ports to measure the axial pressure profile without and with TAN operation. The axial pressure profile data helped anchor CFD model predictions. The use of platelet technology was critical in the design of the TAN injector since the use of conventional manufacturing techniques would not been permitted such an intricate design. The nozzle extension is a gun drilled design similar to the main combustion chamber with axial pressure ports to help in model anchoring.

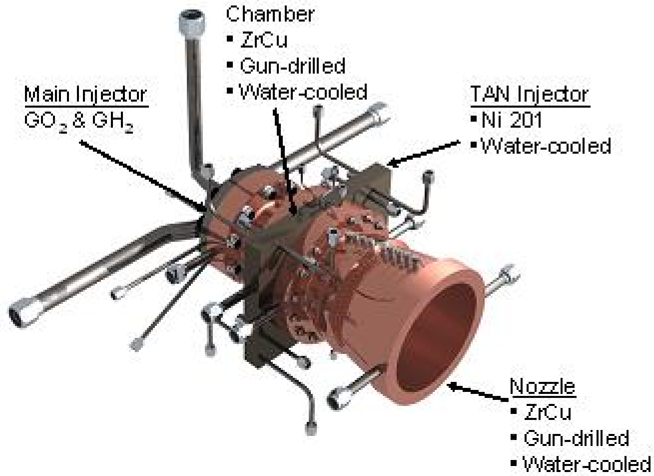

Figure 2. Test Hardware

III. Analysis

The thermal model of the TAN was constructed and analyzed with ANSYS. ANSYS is commercial finite element analysis (FEA) software that can solve many disciplines including both thermal and structural. At Aerojet often the same ANSYS model is used for both the thermal and structural solution. This unified model approach speeds ups the analysis cycle and avoids any costs or issues associated with transferring thermal results from the thermal analyst to the structural analyst. The ANSYS model constructed was the entire length of the TAN injector and symmetry dictated the model size in the circumferential direction. The entire model was approximately 98,000 hex elements and is shown in Fig. 3.

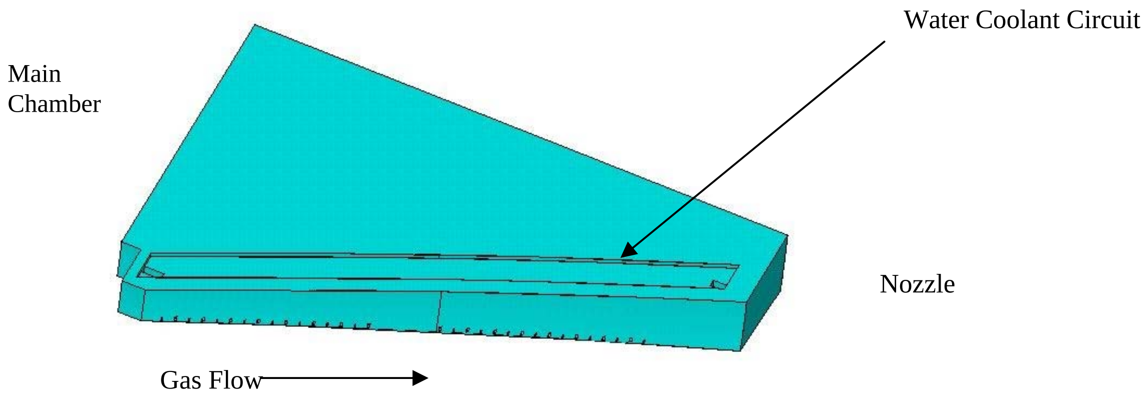

Figure 3. ANSYS TAN Model

The thermal model was analyzed for two set of operating conditions. The first operating condition is where there is no propellant flow through the TAN injector. During this operation condition there is only small purge flow through the TAN propellant circuit to prevent combustion products from entering the TAN propellant circuit. The main injector has been used previously on other test programs and its axial heat flux profile had been previously characterized. For the thermal analysis the previously characterized heat flux profile was used to predict the TAN temperature distribution during the non TAN operation neglecting any impact of the purge flow.

During TAN operation the gas side heat flux was predicted with the aid of computational fluid dynamics (CFD) analysis. CFD two dimensional analysis predicted the axial wall pressure profile for the cases with and without TAN propellant flow. The gas side heat flux was assumed to scale with ratio of wall pressure with TAN operation to wall pressure without TAN operation raised to the exponential power of 0.8. The resulting augmentation to the gas side heat flux ranged from approximately 150% near the head end to about 30% at the aft end of the TAN injector.

The coolant side heat transfer coefficients were modeled with forced convection correlations. Convective heat transfer coefficients were based on the local flow area and hydraulic diameter. For conservatism no enhancement based on entry region or turning was accounted for in the analysis. The water coolant heat transfer coefficients were modeled with the Hines correlation[5]. The water critical heat flux correlation used is a design correlation developed from Aerojet test data for high velocity, high sub cooling water flows[6]. Oxygen heat transfer coefficients were calculated with the Spencer Rousar correlation[7] which was developed by Aerojet during work done for NASA in the 1970s. The heat transfer coefficient for the RP-1 flow was calculated with the Hines correlation.

The TAN injector temperature profile is shown in Fig. 4 with a maximum temperature of 1407 °F. The maximum temperature occurs in an area reserved for pressure ports which are furthest away any water cooling or propellant flow. The maximum heat flux to the water circuit is less than half of the critical heat flux providing adequate margin for testing. The coolant side wall temperature for the RP-1 circuit is below the design coking limit. The maximum TAN injector temperature is predicted to be 1265 °F without any TAN propellant flow as shown in Fig. 5. The maximum temperature for this case occurs at the TAN propellant injection location since they are furthest away from the water cooling circuit.

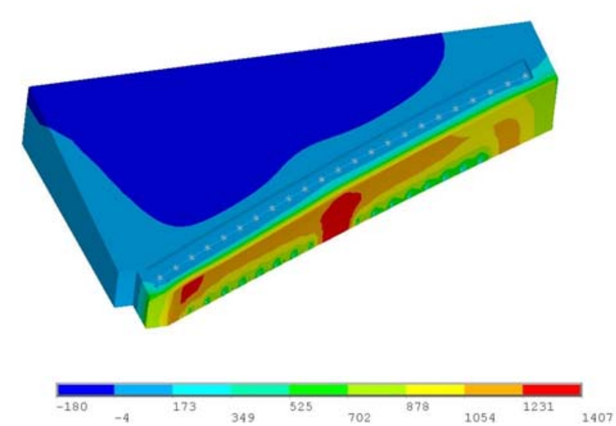

Figure 4. TAN Temperature Prediction (TAN on)

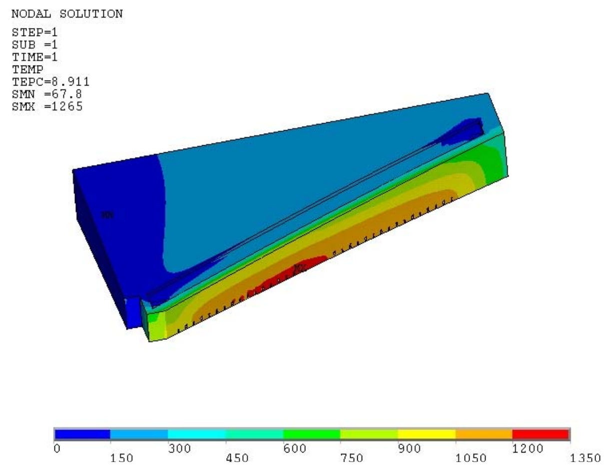

Figure 5. TAN Temperature Prediction (TAN off)

IV. Test Setup and Data Comparison

Testing for the TAN injector occurred in Aerojet Sacramento A-Zone in the summer of 2005 (see Fig. 6). The test series consisted of a total of twenty eights tests. The main chamber pressure, mixture ratio, relative flow rate of the TAN propellants to main chamber were among parameters varied during the test series. The TAN injector was in excellent condition after the test series as shown in Fig. 7. Thermal data gathered during the test series was the measured heat load data for the main chamber, TAN injector, and nozzle. The calculated water flow rate for each component was based on pre test water flow tests for each component. The bulk temperature rise was calculated based on thermocouples located at the inlet and exit of each component.

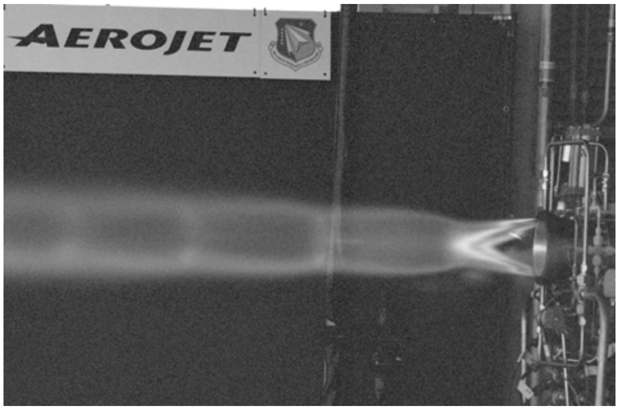

Figure 6. TAN Hot Fire Test at Aerojet's A-Zone

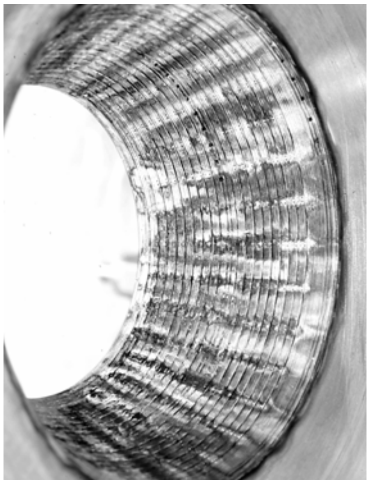

Figure 7. TAN Injector After Hot fire Test Series

The bulk temperature rise of the water coolant for the main chamber was fairly close to pre test predictions since the main injector had been previously characterized. The impact of TAN operation on the main chamber was fairly minimal. Fig. 8 shows the ratio of the heat load with TAN operation to the heat load without TAN operation. The ratio is fairly close to unity indicating minimal to no impact on the chamber section. The heat load in the TAN injector and the nozzle was up to 40% higher with TAN operation as opposed to without TAN operation as shown in Fig. 9 and Fig. 10. The heat load in the sections increased due to increased mass flux. The variation in increase depended on such parameters as the ratio of TAN flow to main chamber flow and main chamber mixture ratio.

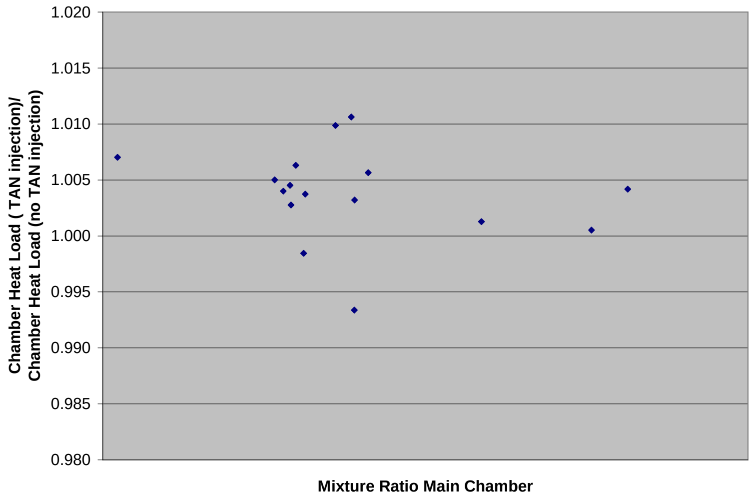

Figure 8. Chamber Heat Load Comparison with and without TAN injection

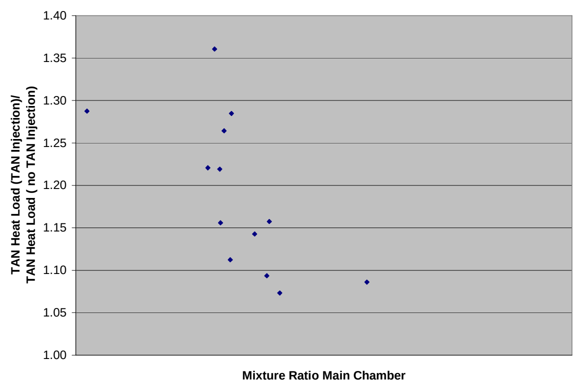

Figure 9. TAN Heat Load Comparison with and without TAN injection

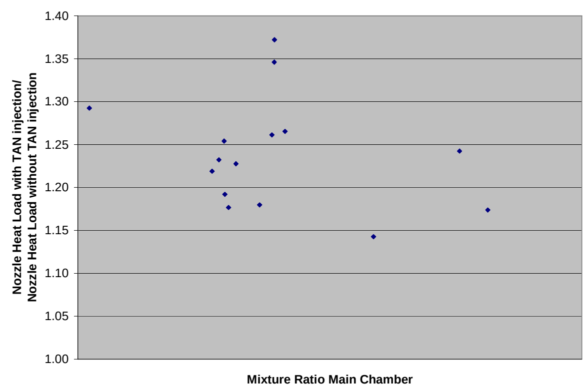

Figure 10. Nozzle Heat Load Comparison with and without TAN injection

V. Conclusions

The TAN concept was successfully demonstrated with subscale testing. Thermal predictions of the TAN injector were done with the aid of CFD analysis. Future work will entail better correlating models with the heat load data for the various test conditions.

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